Introduction to Environmental Geology, 5e

Chapter 6

Earthquakes

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Chapter 6: Overview

- Understand earthquakes, faulting, and estimation of magnitude
- Know earthquake types, seismic risk, and major effects of earthquakes
- Understand earthquake cycles and methods of prediction
- Understand process of hazard reduction and perceived risk to humans

Case History: Earthquake

- On January 12, 2010, a magnitude 7.0 earthquake struck Haiti and killed about 300,000 people
- A magnitude 6.3 earthquake struck the midlevel town of L'Aqila in 2009, many of the buildings collapsed, killing about 300 people.
- In Chili (February 27, 2010), a magnitude 8.8 earthquake, about 500 times as strong as the Haiti earthquake, killed about 800 people
- Buildings are not designed to withstand shaking or are built improperly, causing far more deaths

Earthquakes

- Violent ground-shaking phenomenon by the sudden release of strain energy stored in rocks
- One of the most catastrophic and devastating hazards
- Globally, most earthquakes are concentrated along plate boundaries
- USGS estimated about 1 million quakes annually
- Millions of people killed and billions of dollars in damage by catastrophic earthquakes

Selected Major Earthquakes in the U.S.

TABLE 6.1 Selected Major Earthquakes in the United States

Year	Location	Damage (millions of dollars)	Number of Deaths
1811–1812	New Madrid, Missouri	Unknown	Unknown
1886	Charleston, South Carolina	23	60
1906	San Francisco, California	524	700
1925	Santa Barbara, California	8	13
1933	Long Beach, California	40	115
1940	Imperial Valley, California	6	9
1952	Kern County, California	60	14
1959	Hebgen Lake, Montana (damage to timber and roads)	11	28
1964	Alaska and U.S. West Coast (includes tsunami damage from earthquake near Anchorage)	500	131
1965	Puget Sound, Washington	13	7
1971	San Fernando, California	553	65
1983	Coalinga, California	31	0
1983	Central Idaho	15	2
1987	Whittier, California	358	8
1989	Loma Prieta (San Francisco), California	5,000	62
1992	Landers, California	271	1
1994	Northridge, California	40,000	57
2001	Seattle, Washington	2,000	1
2002	South-central Alaska	(sparsely populated area)	0

Table 6.1

Causes for Earthquakes

- Stress and strain…exerted pressure.
- Stress: A force exerted per unit area within rocks or other Earth materials
- Strain: Deformation (size, shape, and orientation) of rock materials caused by stress
- Rock strength: Rock's ability to stand a magnitude level of stress before rupture
- Earthquake: Strain accumulated beyond rock strength producing eventual release of energy

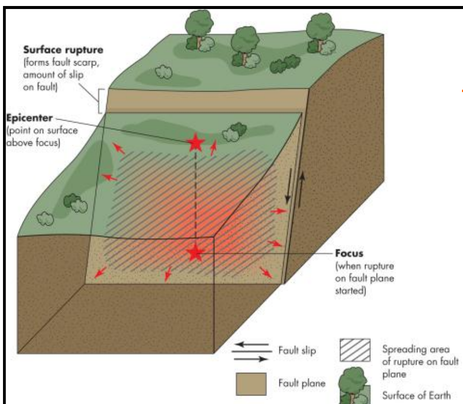
Causes for Earthquakes

Earthquake: Sudden release of strain energy caused by rock rupture (through faulting)
- Brittle deformation

Earthquakes induced by human activities:
- Much smaller magnitude
- Reservoir-induced earthquakes
- Deep waste disposal and earthquake
- Nuclear explosions (underground testing)

Earthquake Magnitude

- **Focus:** The point at depth where the rocks ruptured to produce the earthquake.
- **Epicenter:** The location on the surface of Earth above the **focus.**
- **Moment magnitude:** Measure of the energy released by the earthquake. Estimated by examining the records from seismographs. More appropriate for large EQs.
- ***Richter magnitude:*** Describes the energy released by an earthquake. It is based upon the amplitude or size of the largest seismic wave produced by an earthquake.



Focus

Epicenter

Fault

Fault plane

Figure 6.3

Earthquake Magnitude Scale

- Richter scale: amplitude of ground motion-
  - Increasing one order in magnitude = tenfold increase in amplitude
- Moment magnitude scale:
  - Measuring the amount of strain energy released
  - Based on the amount of fault displacement
  - Applicable over a wider range of ground motions than the Richter scale
- Earthquake energy: Increase one order in magnitude, about a 32-times increase in energy

TABLE 6.2 Worldwide Magnitude and Frequency of Earthquakes, by Descriptor Classification

Descriptor	Magnitude	Average Annual Number of Events
Great	8 and higher	1
Major	7–7.9	18
Strong	6–6.9	120
Moderate	5–5.9	800
Light	4–4.9	6,200 (estimated)
Minor	3–3.9	49,000 (estimated)
Very minor	<3.0	Magnitude 2–3, about 1,000 per day
		Magnitude 1–2, about 8,000 per day

U.S. Geological Survey. 2000. *Earthquakes, Facts and Statistics.* http://neic.usgs.gov. Accessed 1/3/00.

Earthquake Intensity Scale

Modified Mercalli Scale
- Qualitative severity measurement of damages and ground movement
- Based on ground observations, instead of instrument measurement
- Scale depending on earthquake's magnitude, duration, distance from the epicenter, site geological conditions, and conditions of infrastructures (age, building code, etc.)

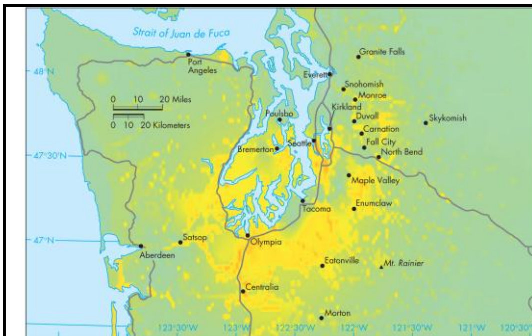
TABLE 6.4 Modified Mercalli Intensity Scale (abridged)

Intensity	Effects
I	Felt by very few people.
II	Felt by only a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration feels like the passing of a truck.
IV	During the day, felt indoors by many, outdoors by few. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound; sensation like heavy truck striking building; standing motor cars rock noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows, and so on broken; a few instances of cracked plaster; unstable objects overturned; disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage is slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving cars.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures; panel walls thrown out of frame structures; fall of chimneys, factory stacks, columns, monuments, walls; heavy furniture overturned; sand and mud ejected in small amounts; changes in well water; disturbs persons driving cars.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings are shifted off foundations. Ground cracked conspicuously. Underground pipes are broken.
X	Some well-built wooden structures destroyed; most masonry and frame structures with foundations destroyed; ground badly cracked. Rails bent. Landslides considerable from riverbanks and steep slopes. Shifted sand and mud. Water is splashed over banks.
XI	Few if any (masonry) structures remain standing. Bridges are destroyed. Broad fissures are formed in ground. Underground pipelines are taken out of service. Earth slumps and land slips on soft ground occurs. Train rails are bent.
XII	Damage is total. Waves are seen on ground surfaces. Lines of sight and level distorted. Objects are thrown upward into the air.

From Wood and Neuman, 1931, by U.S. Geological Survey, 1974, *Earthquake Information Bulletin* 6(5):28.

USGS Did You Feel It - Intensity

Table 6.4a



Instrumental intensity	I	II-III	IV	V	VI	VII	VIII	IX	X+
Shaking	not felt	weak	light	moderate	strong	very strong	severe	violent	extreme
Damage	none	none	none	very light	light	moderate	moderate/heavy	heavy	very heavy

(b)

Plate Boundary and Earthquakes

- Most earthquakes concentrated along plate boundaries (nearly all catastrophic earthquakes are shallow earthquakes). Some interplate.
- Divergent plate boundary: Shallow earthquakes
- Transform plate boundary: Shallow to intermediate earthquakes
- Convergent plate boundary: Wide zone of shallow, intermediate, and deep earthquakes.
  - ~ 80% of seismic energy released along the earthquake zone around the Pacific rim.

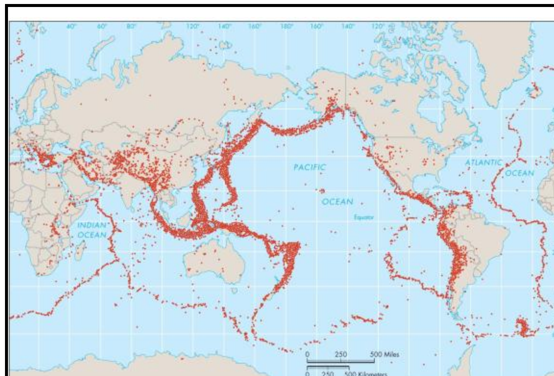


Figure 6.5

Major Intraplate Earthquakes

Intraplate earthquakes: earthquakes occurs within the plate, away from plate boundaries.

- In the eastern United States are generally more damaging due to stronger rocks that transmit earthquake waves more efficiently than rocks in the west.
- Even in the "stable" interior of the North American plate, the possibility of future damage demands that the earthquake hazard should be considered when constructing power plants and dams.

Major Intraplate Earthquakes

1811-1812 New Madrid earthquake; M >8.0

- Destroyed New Madrid, unknown loss of life
- Rang church bells as far away as Boston
- Forests flattened

1886 Charleston earthquake; M 7.5

- Killed 60 people
- Damaged or destroyed most buildings
- Impacted area beyond 1000km (620mi)

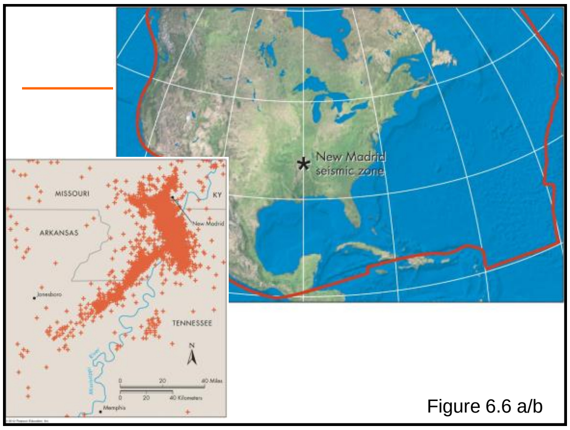


Figure 6.6 a/b

Earthquake Processes

- Fault types: dip-slip (normal, reverse, thrust) and strike-slip (left- or right-lateral)
- Fault activity: active, potentially active (1.65mya-10k), and inactive (prior to 1.65mya)
- Fault-related tectonic creep
- Slip rate: The long-term rate of movement, recorded as millimeters per year (mm/yr) or meters per 1,000 years (m/ky)

Locations:

- Global plate boundaries
- Regional
- Local

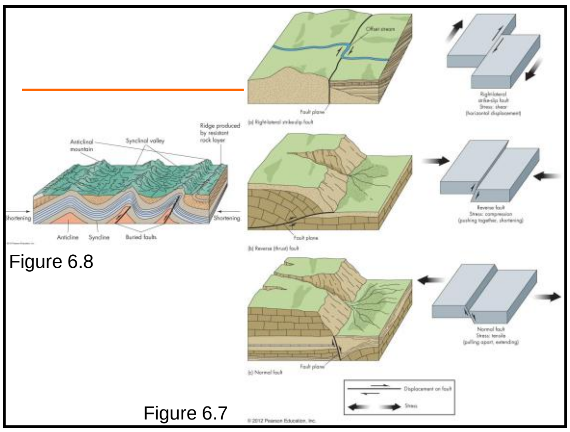


Figure 6.8

Figure 6.7

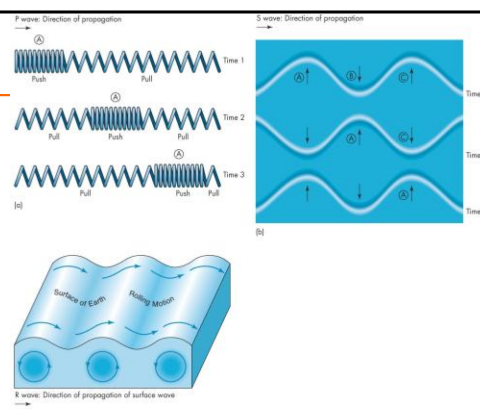
Earthquake Processes

Faults almost never occur as a single rupture. Rather, they form **fault zones.**

- Most long faults or fault zones, such as the San Andreas fault zone, are *segmented*
  - **Earthquake segment:** Part of a fault zone has ruptured as a unit during historic and prehistoric earthquakes.
- **Paleoseismology:** The study of **paleoseismicity** (prehistoric seismic activity) from the geologic environment.

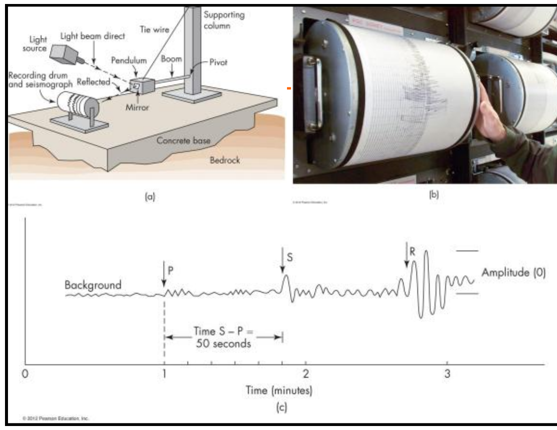
Seismic Waves

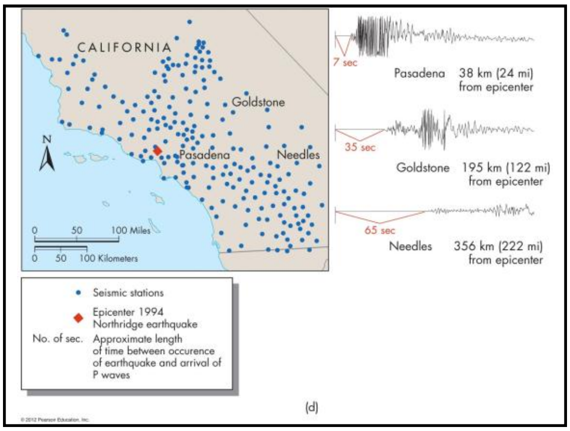
- Generated from the earthquake focus
- P-waves: compression waves, travel faster through all physical states of media
- S-waves: shear waves, travel slower than P waves, but faster than surface waves, only propagate through solid materials
- Surface waves: moving along Earth's surface, travel slowest, but cause most of the damage



Measuring Seismic Waves

- Seismograph or seismometer: Device to record the seismic waves
- Seismogram: The record of an earthquake
- Amplitude of seismic waves: Amplitude of ground vibration. (wave height)
- First arrival of seismic waves
  - Determine the time of earthquake
  - Distance to epicenter from a seismograph based on the difference in arrival time between P waves and S waves





Material Amplification

- Seismic waves travel differently through different rock materials.
  - Propagate faster through dense and solid rocks
- Material amplification: Intensity (amplitude of vertical movement) of ground shaking more severe in unconsolidated materials.
  - Seismic energy attenuated more and propagated less distance in unconsolidated materials
- Directivity: Another amplification effect, the intensity of seismic shaking increases in the direction of the fault rupture

Material Amplification

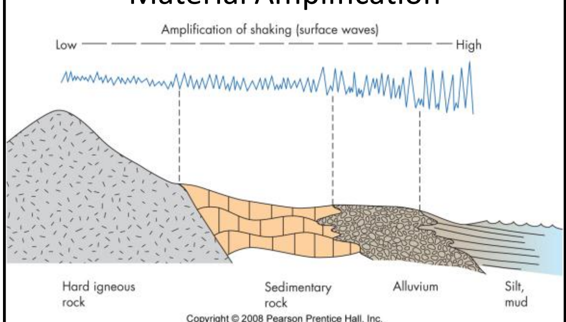
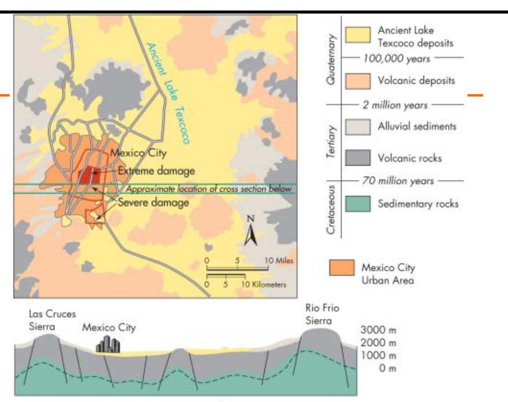


Figure 6.13



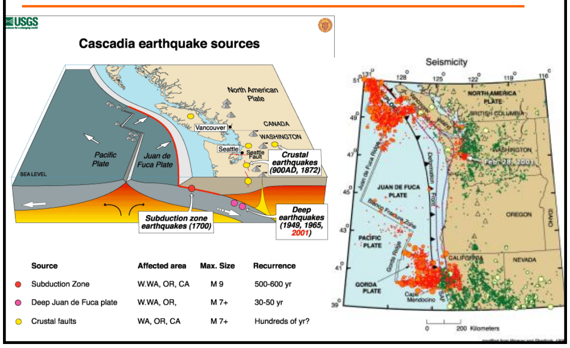
(b)

Figure 6.14

Ground Acceleration

- Ground motion is related to the amplitude of seismic waves and its accelerations.
  - Acceleration is the rate of velocity change with time.
- Measured by accelometers in terms of the acceleration of gravity -(1g) is equal to 9.8 m/sec^2
- Both vertical and horizontal accelerations
- M 6.0 to M 6.9 can have 0.3 to 0.7 g
- Structure designs target to withstand 0.6 to 0.7 g

Earthquakes and Depth of Focus



Earthquake Cycles

- Elastic strain – non-permanent deformation.
- Elastic rebound – 'snap' of rocks back to original shape as elastic strain is recovered.

Stages of earthquake cycle:

- Aftershock stage and inactivity
- Stress accumulation stage
- Foreshocks
- Main shock (major earthquake)

Effects of Earthquakes

Primary Effects –

- Ground shaking, tilting, and ground rupture
- Loss of life and collapse of infrastructure

Secondary Effects –

- Landslides, liquefaction, and tsunamis
- Fires, floods, and diseases

Tertiary Effects –

- Social and psychological impacts

Figure 6.23

(b)

Figure 6.20a

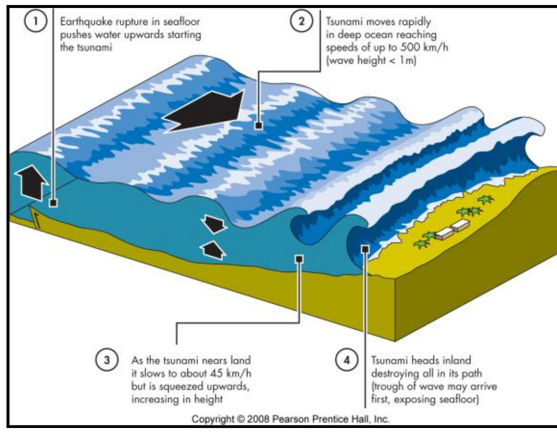
Figure 6.24

Figure 6.26

Figure 6.27

Effects of Earthquakes: Tsunami

- Triggered by earthquake, submarine volcanic eruption, underwater landslide, asteroid impact
- Recent tsunami examples:
  - 1883 Eruption of Krakatoa, 36,000 deaths
  - 1960 (M 9.5) Chile earthquake, 61 deaths in Hawaii
  - 1964 (M 9.2) Alaska earthquake, 130 deaths in AK/CA
  - 1993 (M 7.8) earthquake Japan, 120 deaths in Japan
  - 1998 (M 7.1) Papua New Guinea earthquake, 2100 deaths
  - 2004 (M 9.1) Indonesian earthquake, about 230,000 deaths
  - 2010 (M 8.8) Chile earthquake, about 20 coastal deaths
  - 2011 (M 9.0) Japan earthquake, about 15,700 deaths



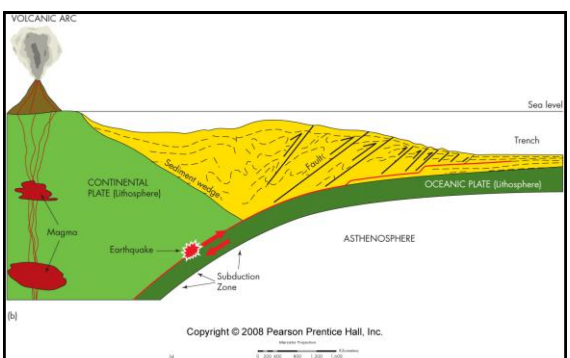
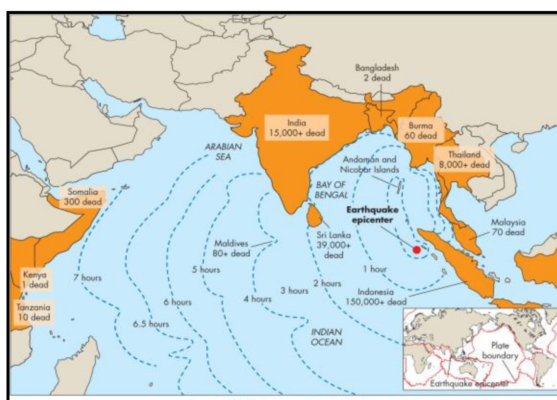


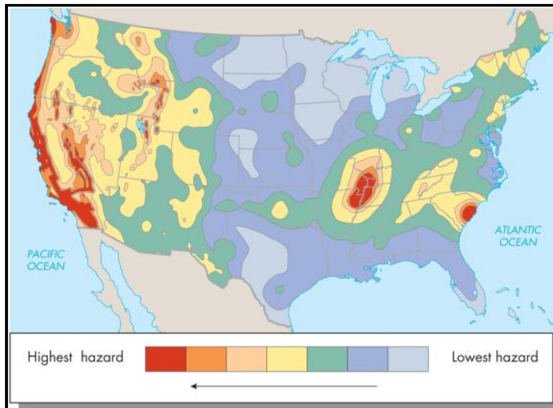
Figure 6.A B, 4th edition



Earthquake Risks

- Probabilistic methods for a given magnitude or intensity of a period of time
- Earthquake risk of an area
- Earthquake risk of a fault segment
- Possible sequencing of earthquakes on segments along a fault?

Construction of seismic hazard maps
Conditional probabilities for future earthquakes



Earthquake Prediction

- Long-term prediction
  - Earthquake hazard risk mapping
- Short-term prediction (forecast)
  - Frequency and distribution pattern of foreshocks
  - Deformation of the ground surface: Tilting, elevation changes
  - Emission of radon gas
  - Seismic gap along faults
  - Abnormal animal activities?

Figure 6.17

Figure 6.35, 4th edition

Response to Earthquake Hazards

Hazard Reduction Programs:

- Develop a better understanding of the source and processes of earthquake
- Determine earthquake risk potential
- Predict effects of earthquakes
- Apply research results

Response to Earthquake Hazards

Adjustments to earthquake activities:

- Site selection for critical facilities
- Structure reinforcement and protection
- Land-use regulation and planning
- Emergency planning and management: Insurance and relief measures

Earthquake Warning Systems

- Technically feasible: ~ 1 minute warning
- Network of seismometers, sensing the first earthquake motion and sending a warning to critical facilities and public
- Warning system
  - Not a prediction tool
  - Can create a false alarm
- Better prediction and better warning system?

Perception of the Earthquake Hazard

- Public education and preparedness for the earthquake potential, even psychologically
- Pre-earthquake planning: what to do when struck
- During-earthquake: understand the situation and formulate a good strategy
- Post-earthquake emergency response
- Better engineering structural designs to minimize the future hazard risks

Applied and Critical-Thinking Topics

- What is the main lesson from the recent earthquakes in Italy and Haiti? How important is the wealth of a country to reducing the earthquake hazard?
- From your point of view, what can an individual citizen do to minimize the earthquake impact risks?
- What would be your approach to present info on earthquake hazard to people who knew very little about earthquake?
- Propose geologic scenarios that may change the global earthquake distribution patterns.